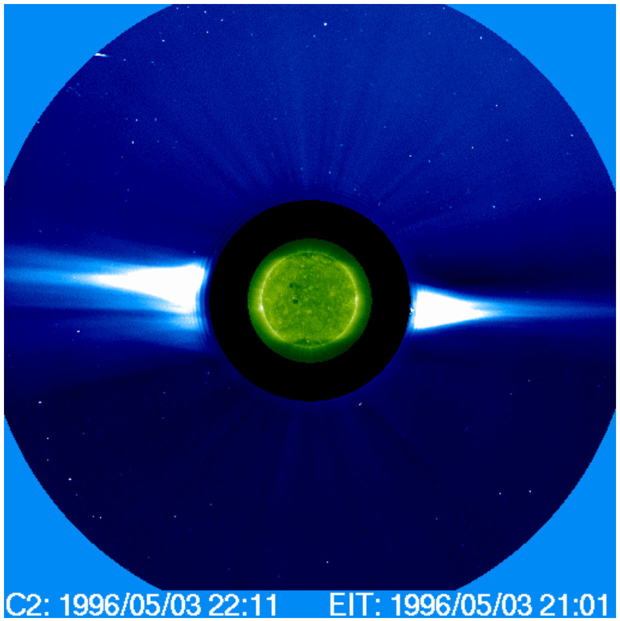
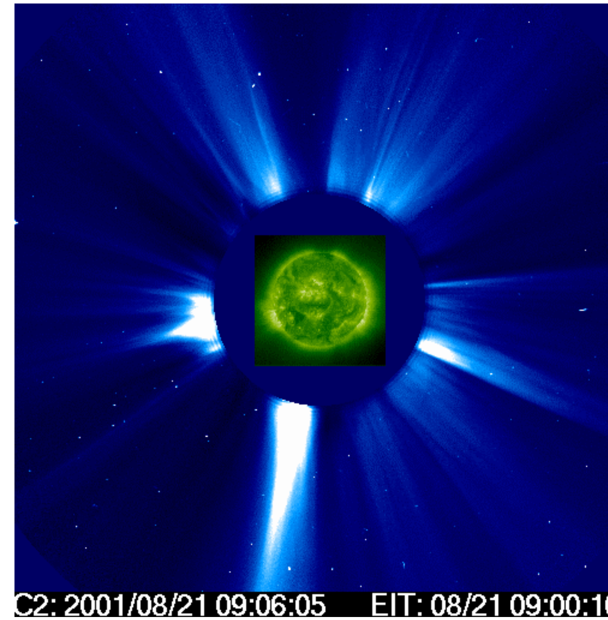
Coronal Mass Ejections of Solar Cycle 23





Nat Gopalswamy (NASA/GSFC)

September 12, 2003

SEC seminar

Thanks to…

- The LASCO team
- LASCO operations scientists who produced preliminary lists of CMEs (O. C. St. Cyr, S. P. Plunkett, G. Lawrence)
- The CME catalog team (E. Aguilar-Rodriguez, G. Michalek, S. Nunes, N. Rich, A. Rosas, G. Stenborg, S. Yashiro)
- Collaborators: A. Lara, R. Howard, M. Shimojo, K. Shibasaki

In this talk…

- CME rate (daily rate averaged over Carrington Rotation for the years 1996-2002)
- CME rate and other measures of solar activity (Sunspot number, tilt angle, prominence eruption, polar field strength)
- CME rate and polarity reversal
- Summary
- Will not talk about Special Populations (Halos, FW) – http://cdaw.gsfc.nasa.gov/publications

Data Sources

- CMEs form the SOHO/LASCO catalog: http://cdaw.gsfc.nasa.gov/CME-list
- Tilt angle from

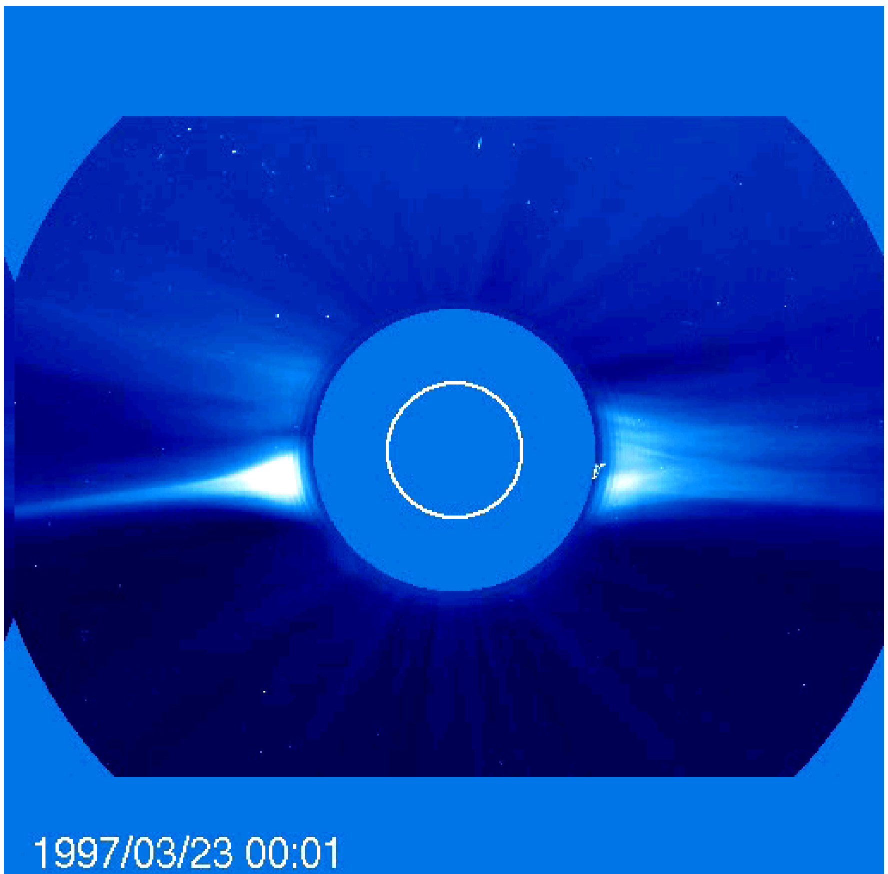
  http://quake.stanford.edu/~wso/Tilts.html
- KPNO magnetic field data
- Prominence Eruption data from the Nobeyama Radioheliograph catalog:

  http://solar.nro.nao.ac.jp

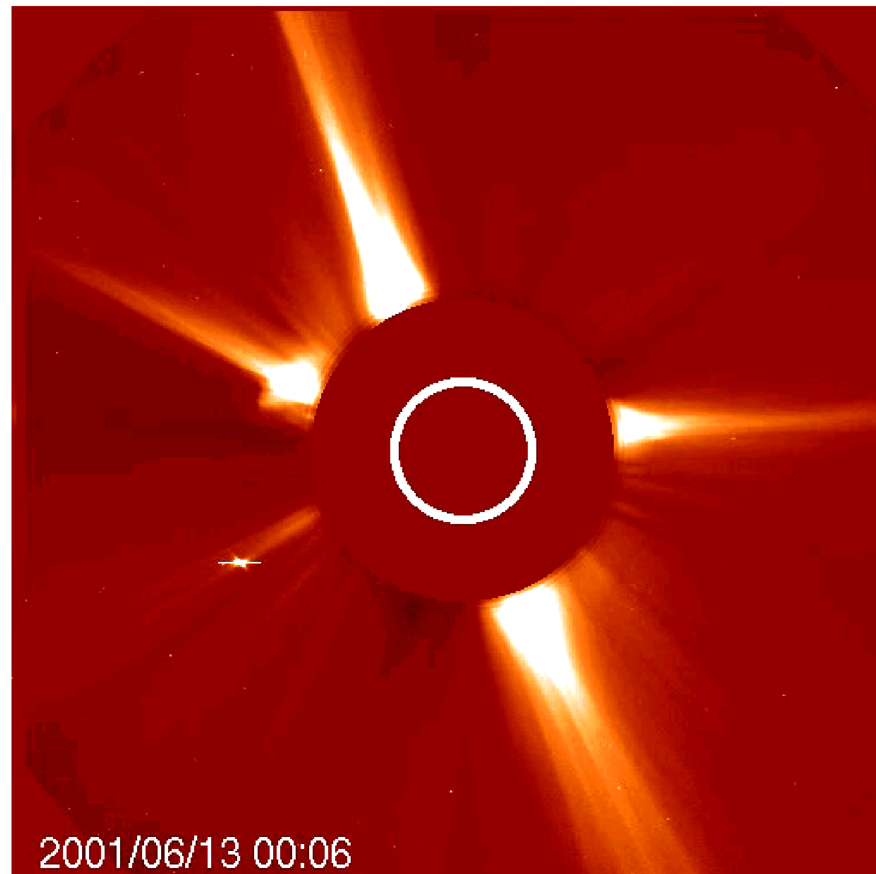
CMEs at minimum and maximum phases:

CMEs occur from closed field regions

Minimum: 1 CME

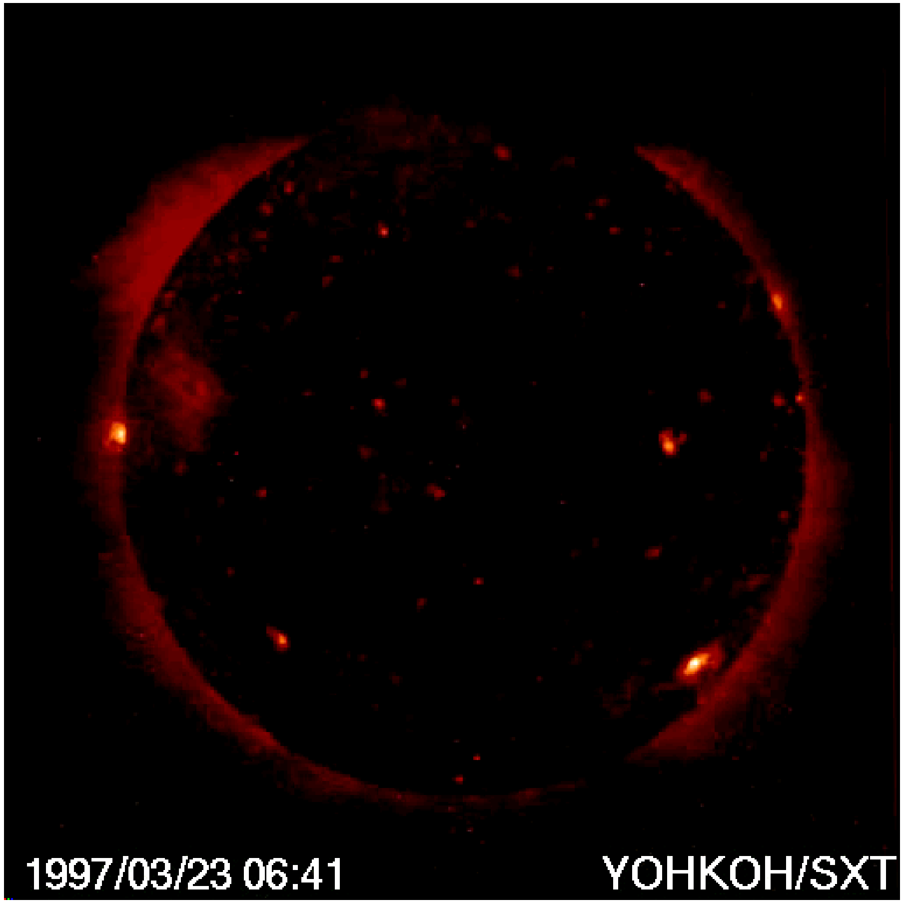


Maximum:12 CMEs

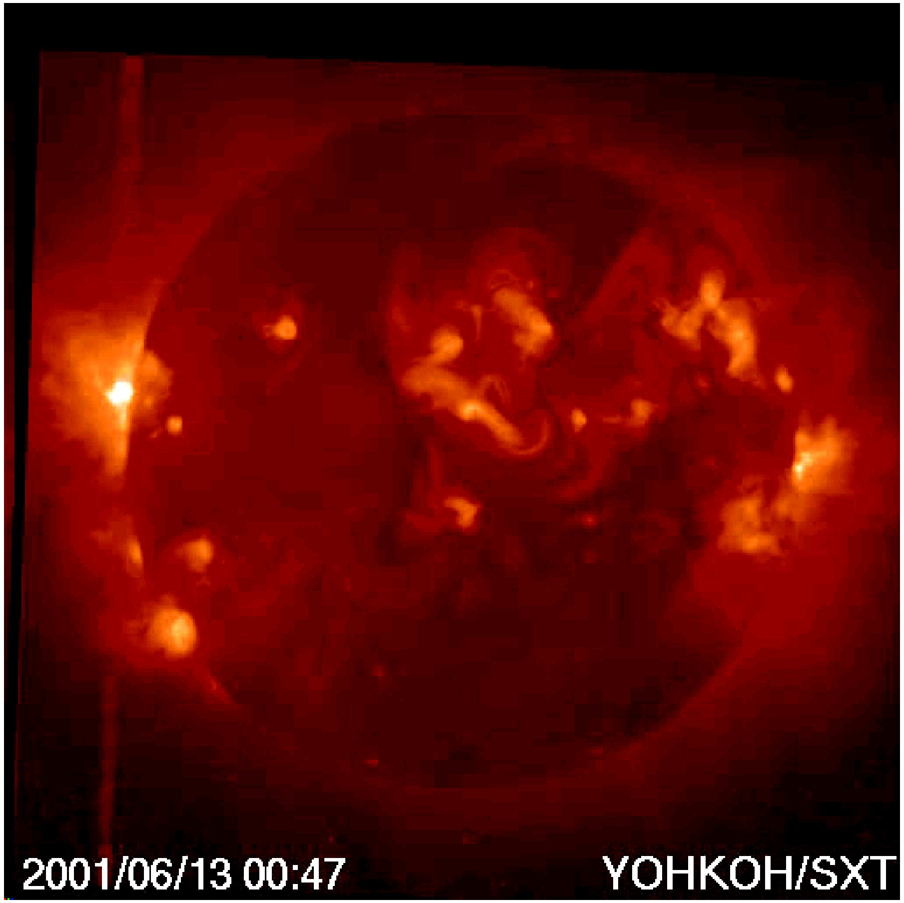


Soft X-ray Corona

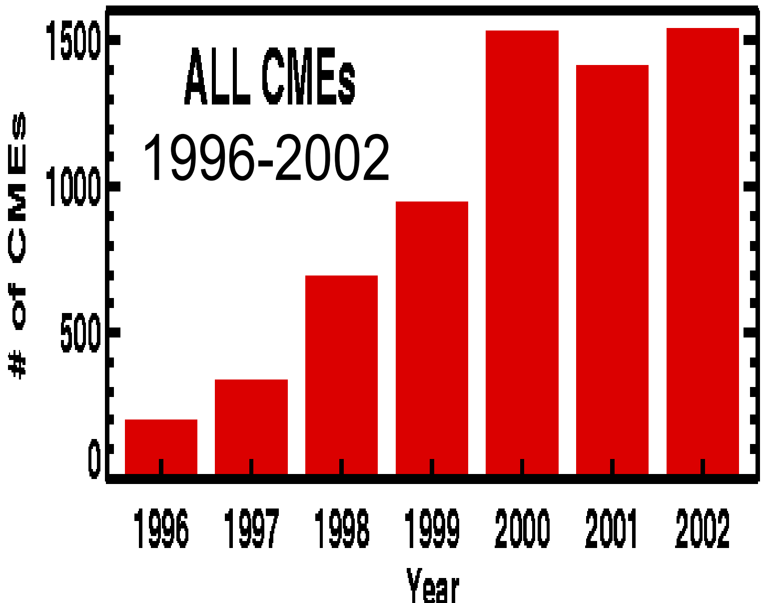
Minimum



Maximum

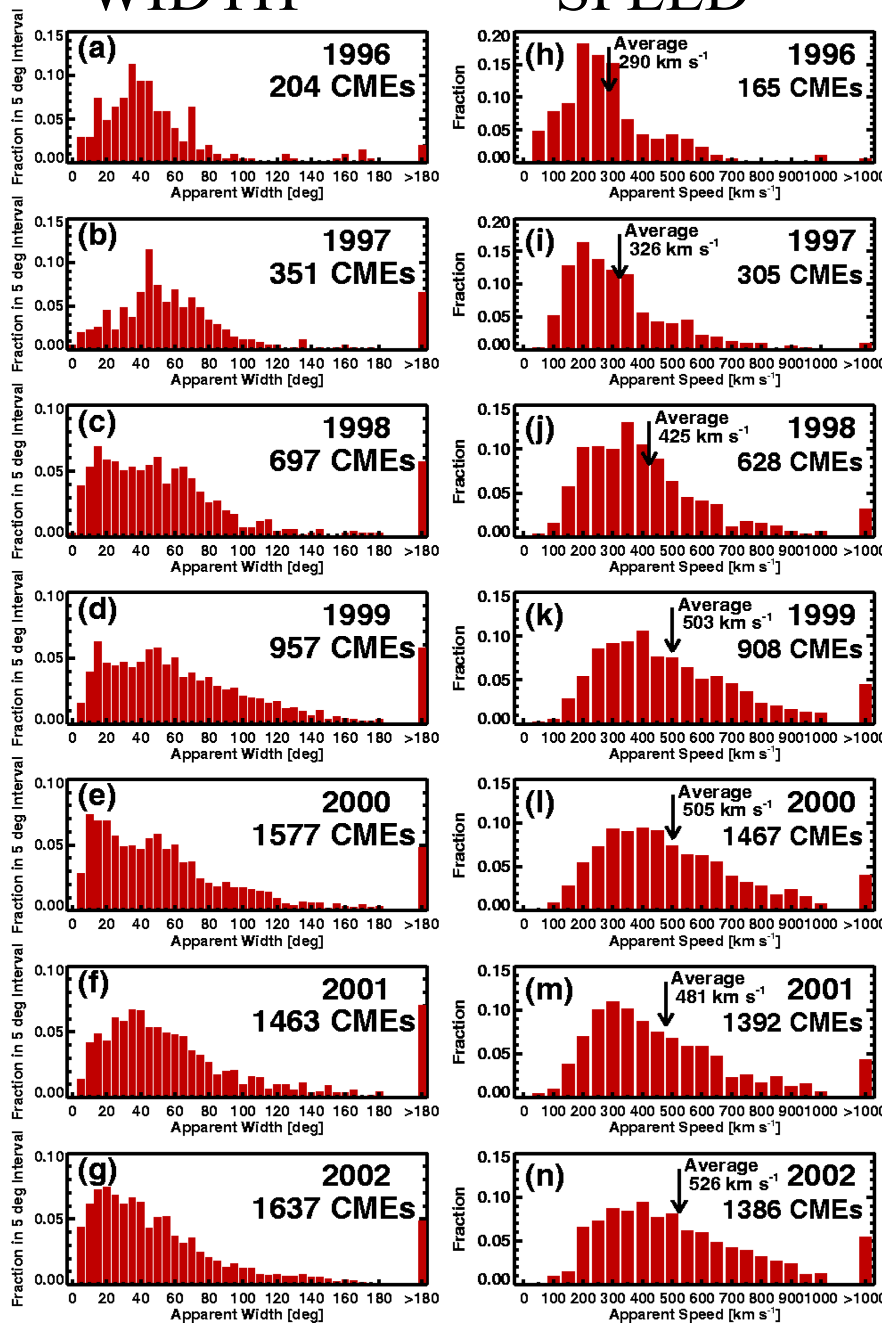


SOHO CMEs: Annual Distributions



204 351 697 957 1577 1483 1637

WIDTH SPEED



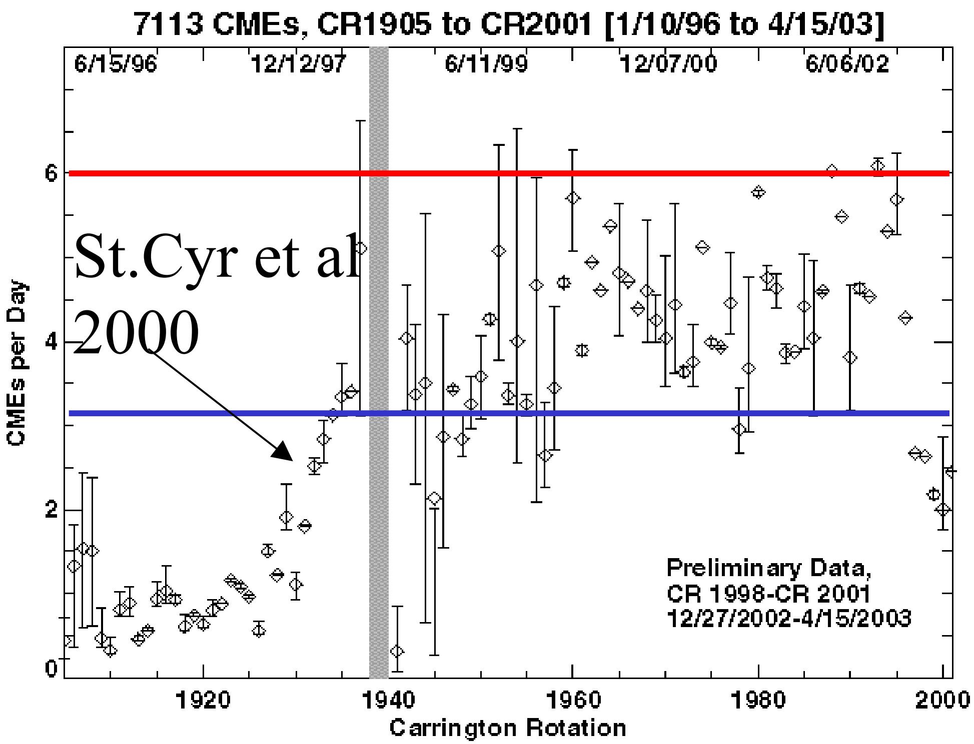
1998 – 3-month gap

1999 – 1-month gap

Highest # & speed in 2002

All CMEs (1996-2002)

→ Averaged over Carrington Rotation period (27.34 days)
→ CMEs/day increased from 1 every other day to > 6 per day
SOHO CME rate is much larger than pre-SOHO rates



T_d = Down time (days) in each CR
T_u = Up time (days) during each CR
R_{max} = Max no. of CMEs per day during a CR
R_{obs} = # CMEs in the CR/T_u

Upper limit to rate:

$(T_u R_{obs} + T_d R_{max})/27.34$

Lower limit: $T_u R_{obs}/27.34$

Max rate from pre-SOHO data

Speed Variability: Solwind & SMM

• "speeds vary widely, even when averaged over intervals as long as a year." Hundhausen (1999)

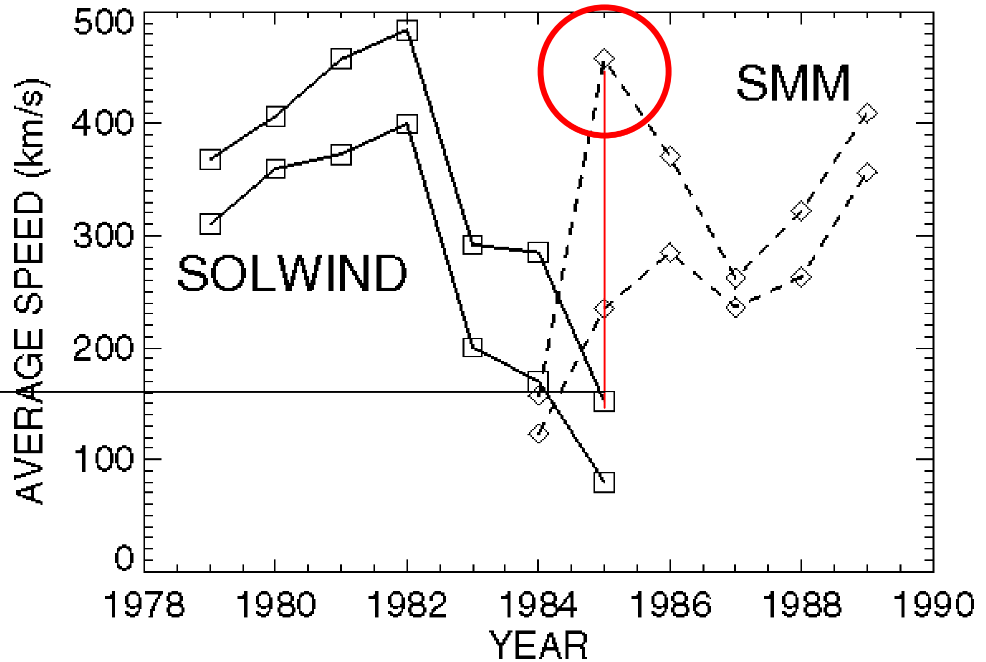
• Webb (1994): Solwind data shows solar cycle variability of CME speed; SMM does not.

• The 1985 SMM point may not be reliable : only 39 of the 62 CMEs had speed measurements. Highest annual average from the entire SMM epoch (458 km/s)

• Solwind average speed is much smaller.

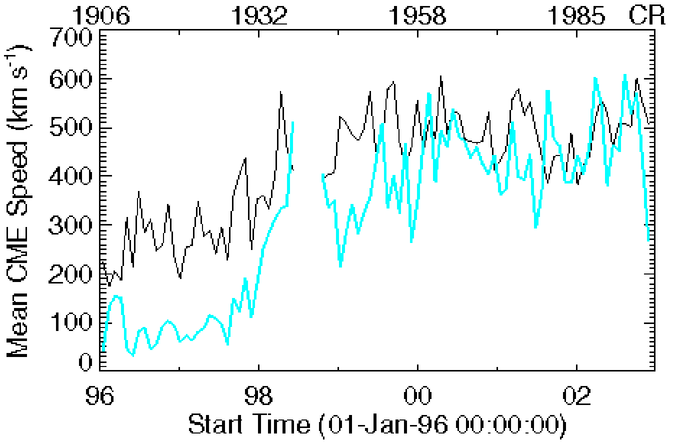
• Apart from this point, the annual average of mean and median speed show solar cycle variation.

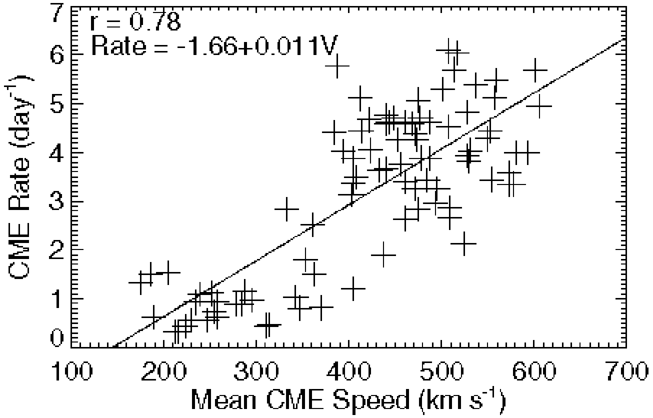
• Ivanov & Obridko (2000) : Semiannual averages of mean speed show a peak near minimum, in addition to the peaks in the maximum epoch (1981-1982, 1989)



1980-1989 data from St. Cyr et al. (1999)
1979 data from Solwind catalog.

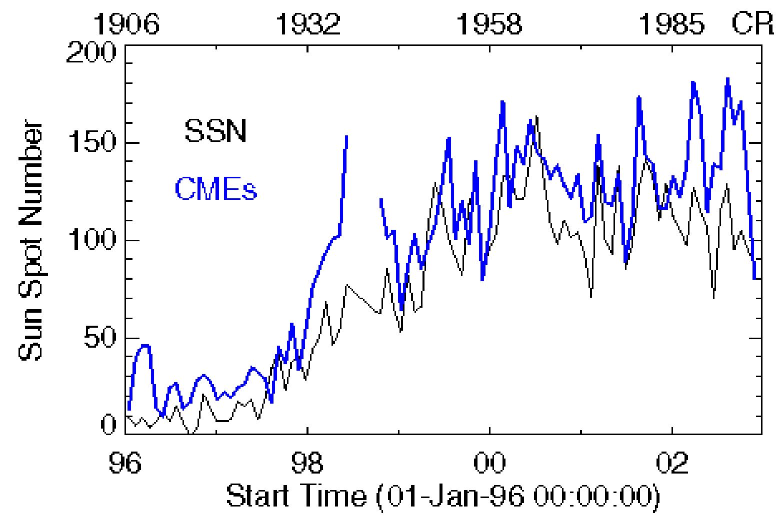
CME speed also increases from Min to Max

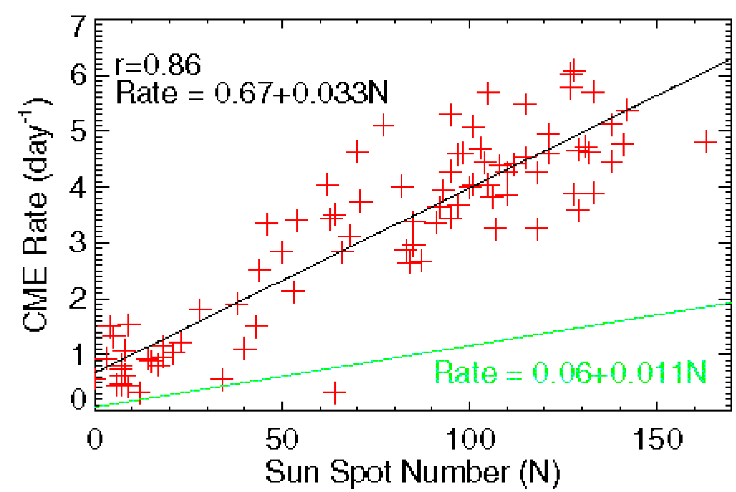




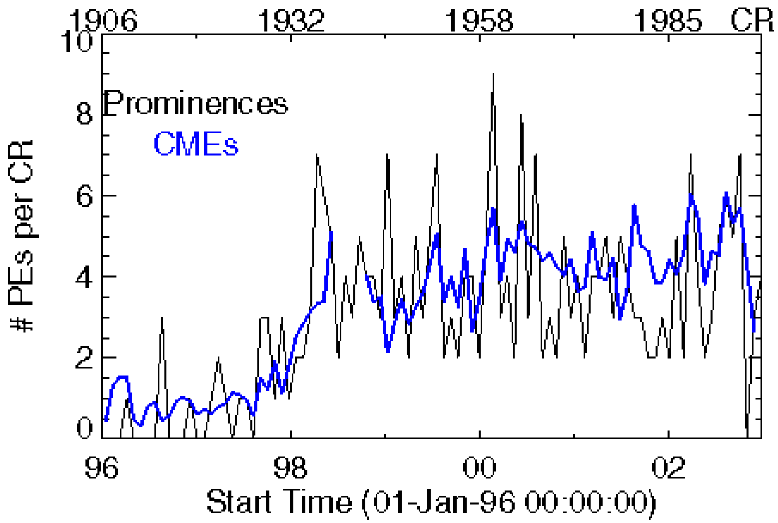
CME Rate & Sunspot Number

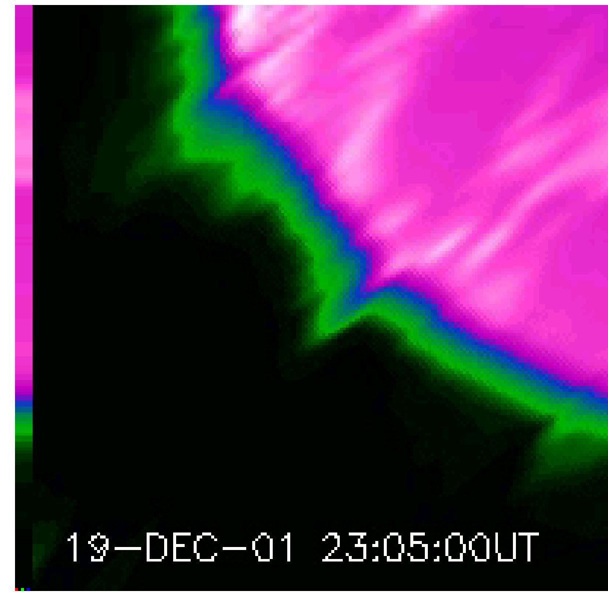
- Hildner et al. (1976) had predicted a peak rate of 3.2 CMEs/day based on Skylab data
- Webb & Howard (1994), Cliver et al. (1994) confirmed this relationship using all available data (1973-1989)
- SOHO data confirms the relationship, but the slope is drastically different, because the peak rate nearly doubled.
- Large scatter for large SSN: Correlation weakens during solar maximum phase

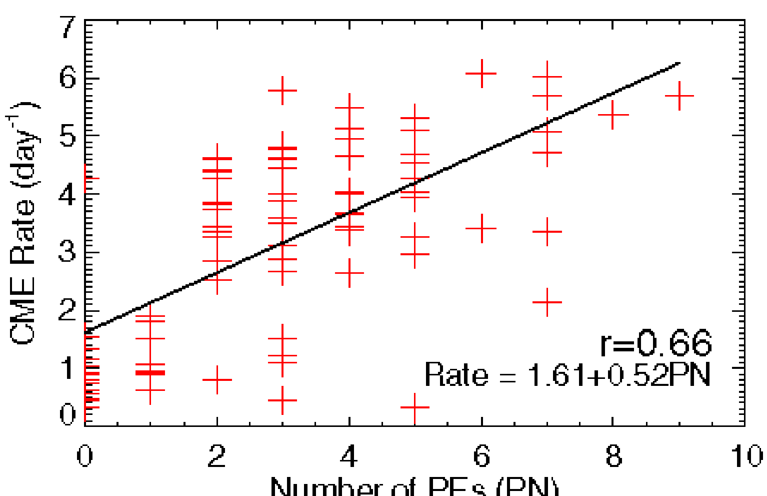


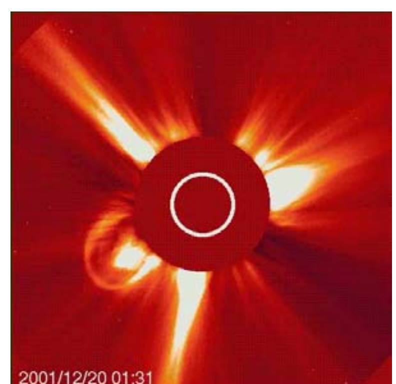


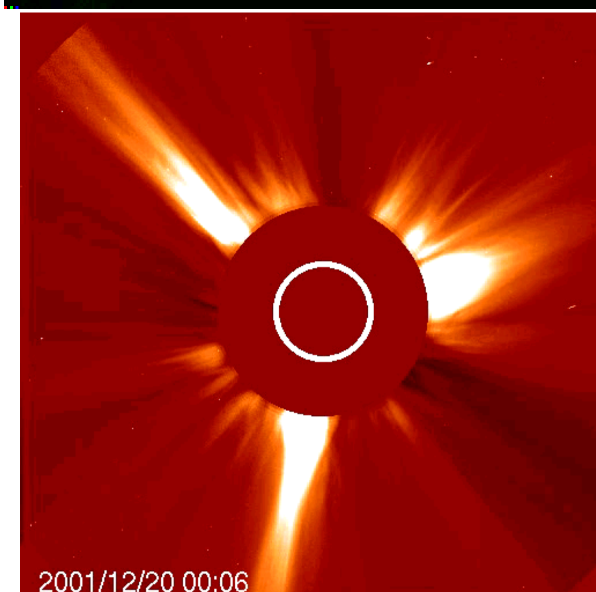
CME Rate and Prominence Eruptions





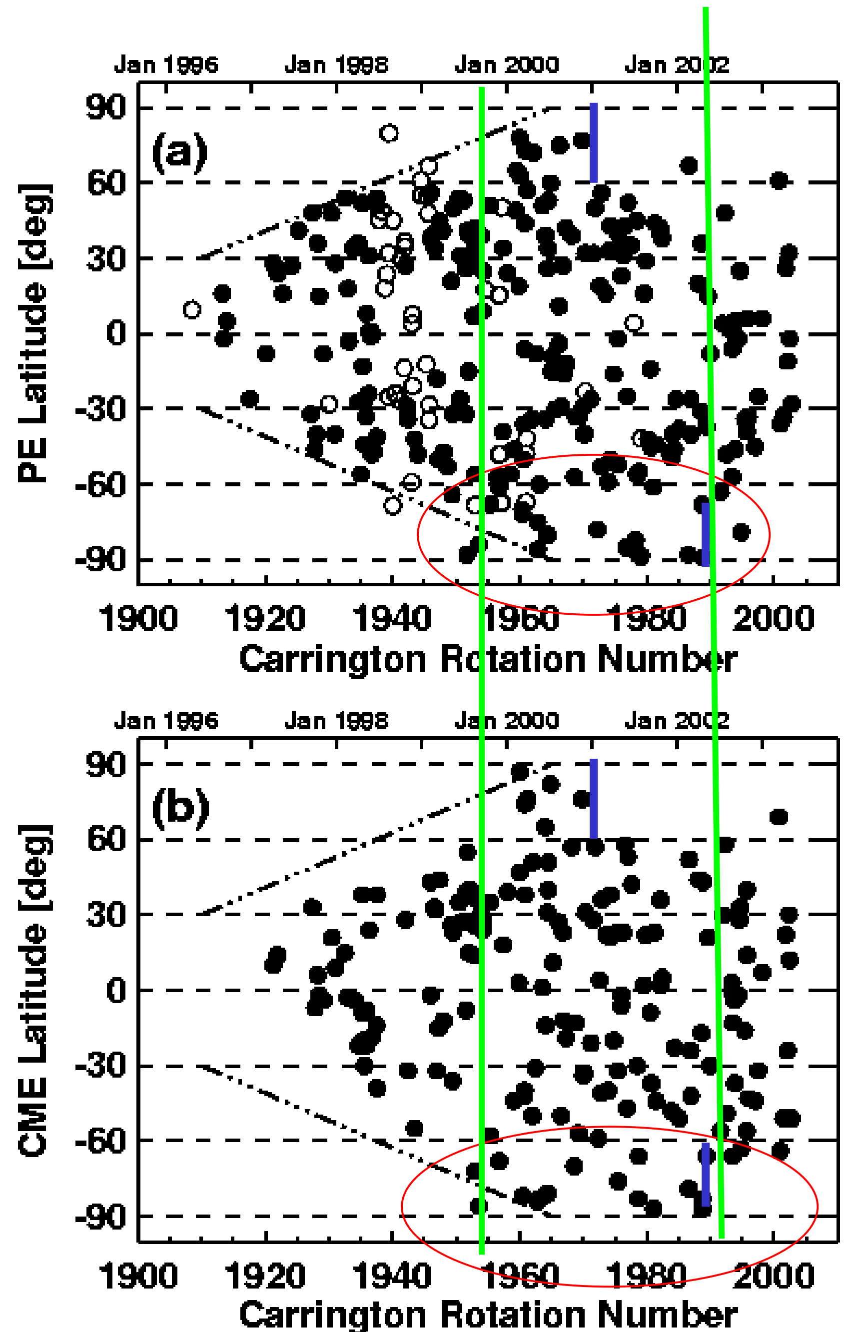






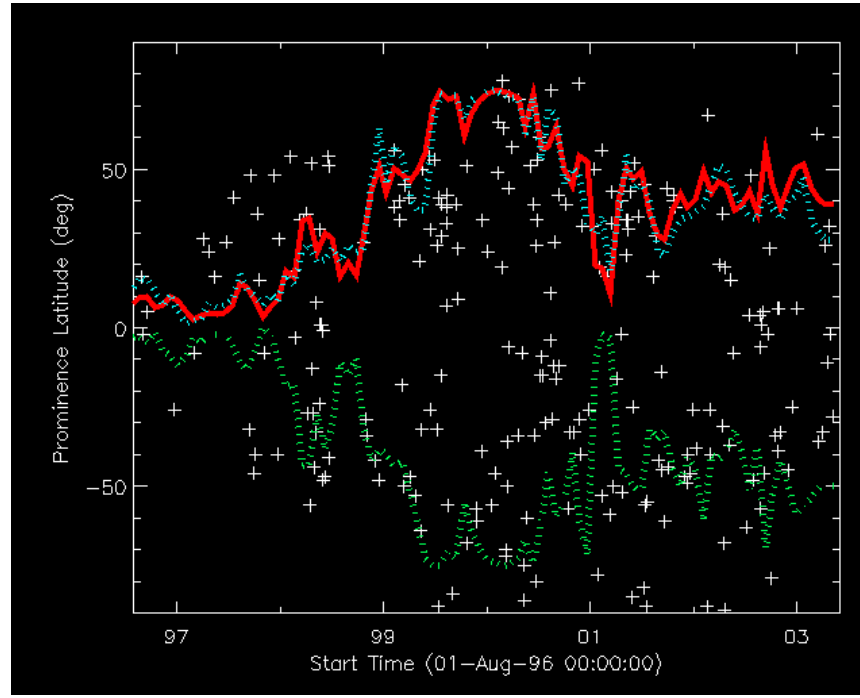
CMEs & Prominences

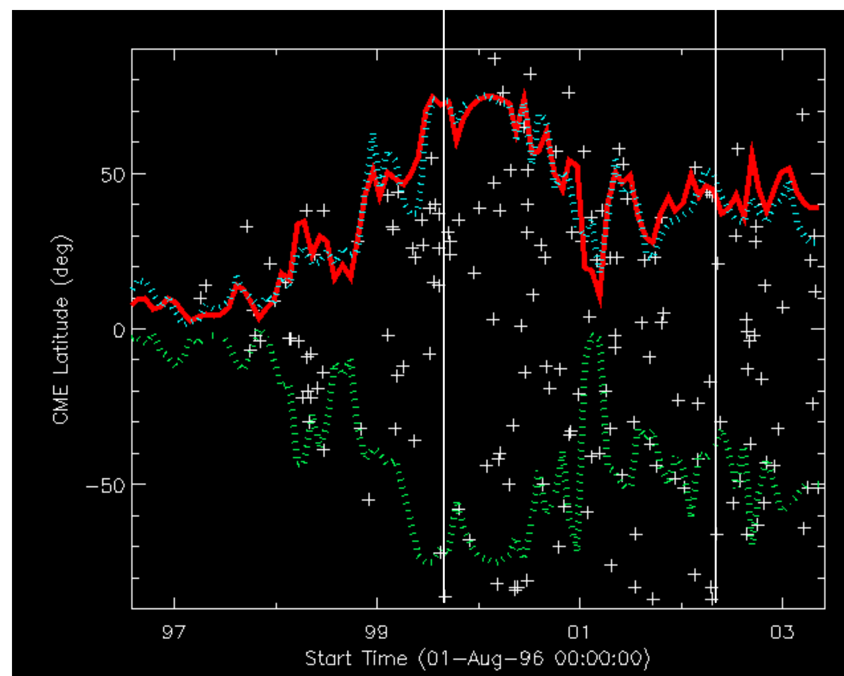
- High latitude (HL) prominence eruptions and CMEs during CR 1950-1990 (mid ’99 – early ’02)
- N-S asymmetry (NHL ends in 11/00; SHL ends in 5/02)
- These CMEs are not associated with sunspot activity



Tilt Angle, CMEs & PEs

- High latitude CMEs and prominence eruptions occur when the tilt angle is large (~ 50 deg)
- CMEs seem to follow the tilt angle better than the PEs do.

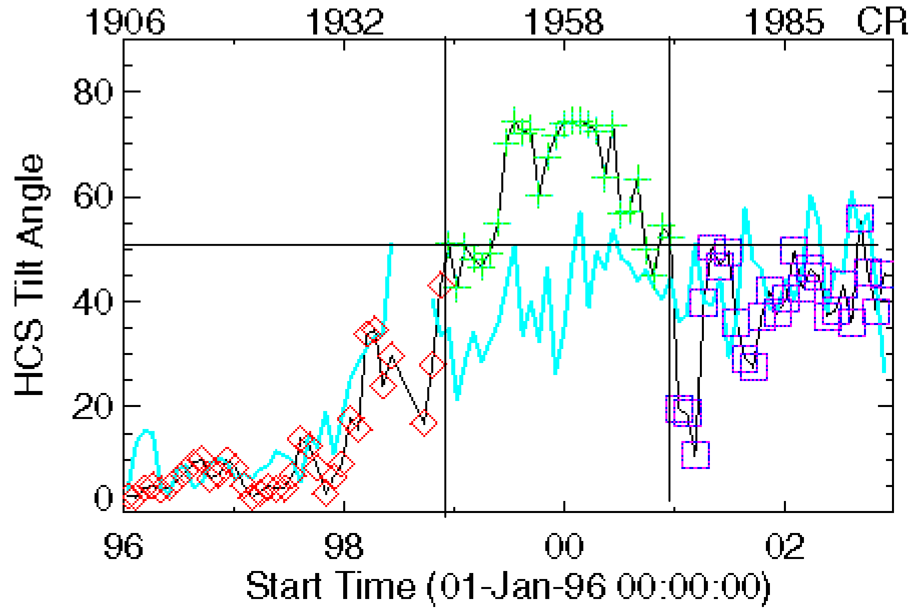


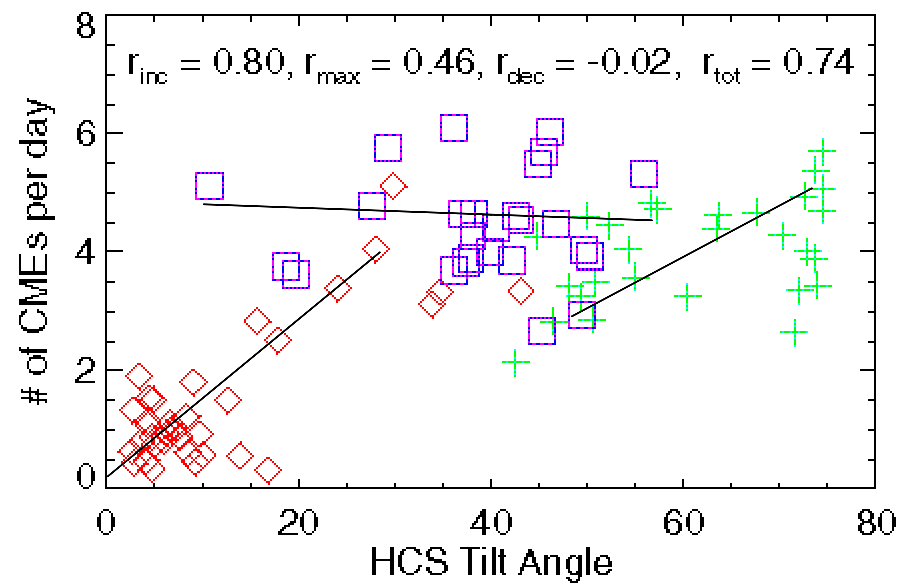


CME Rate as a function of Tilt Angle

- Increasing tilt: CME rate is positively correlated with TA (r = 0.80)
- Max Phase: TA > 50 deg, CME rate weakly correlated with TA (r = 0.46)
- Declining Phase: CME rate not correlated with TA (r = -0.02)

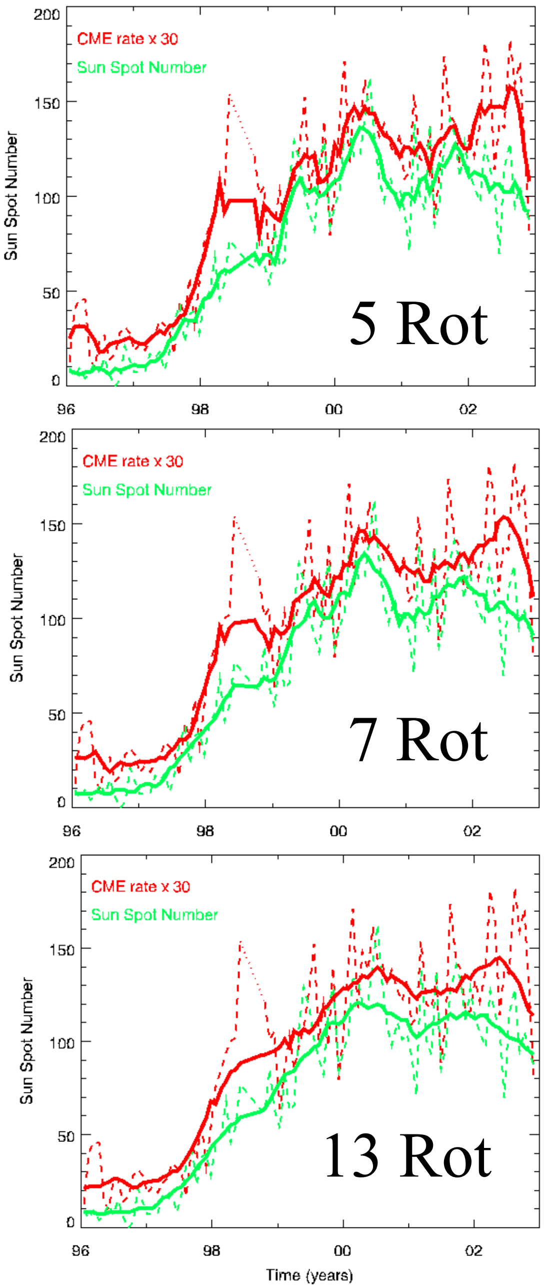
(Rush to the poles: Cliver et al. 1994)



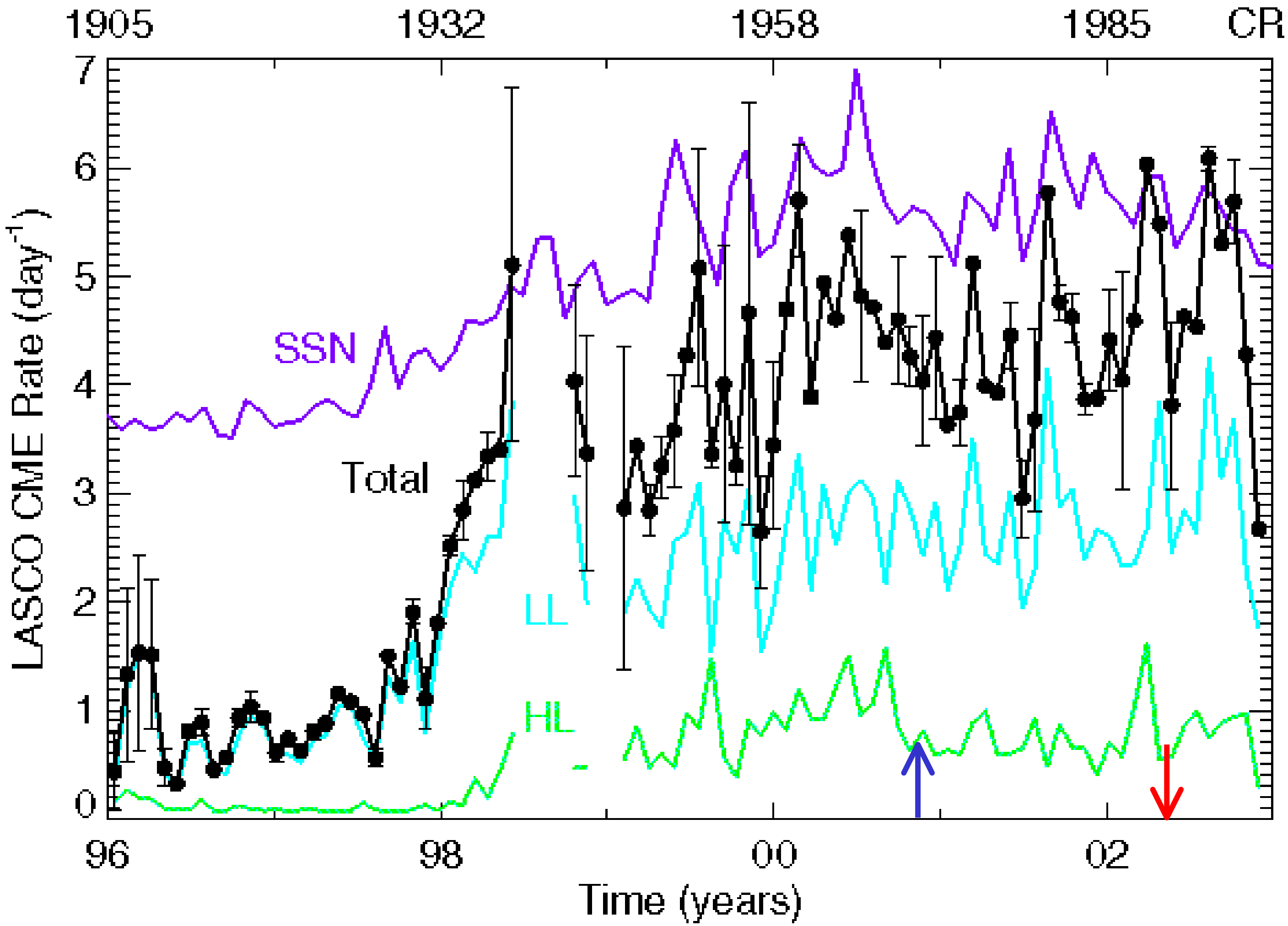


CME Rate & SSN

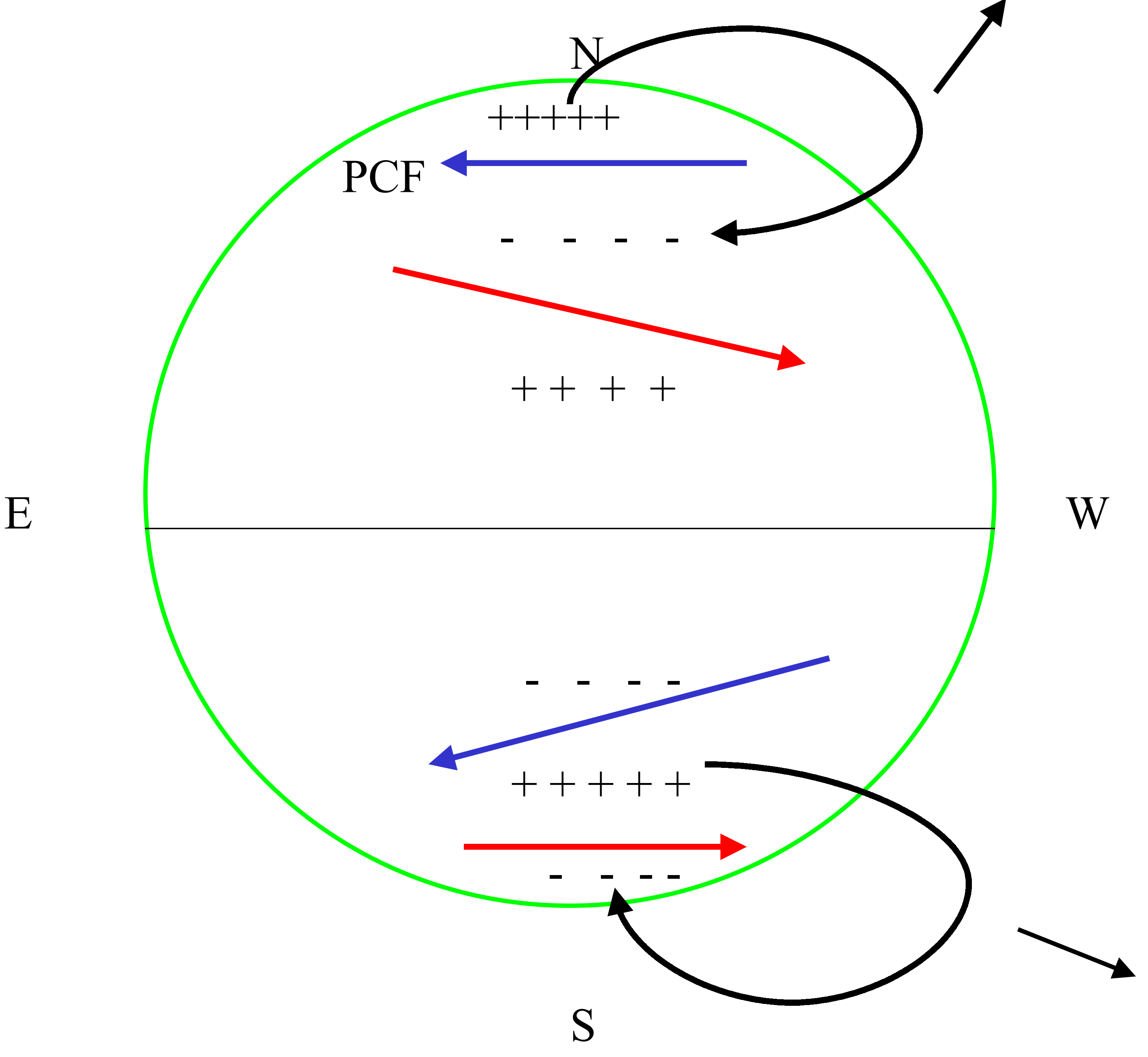
- SSN has double peak (largest in July 2000)
- CME rate peaked in Oct 2002
- The difference persists when smoothed over 5, 7, or 13 rotations



SSN & CME Rates



SSN: Sunspot number; Total: All CMEs; LL-low-latitude CMEs; HL – high-latitude CMEs
Red arrow: reversal at North Pole; Blue arrow: reversal at South Pole



N
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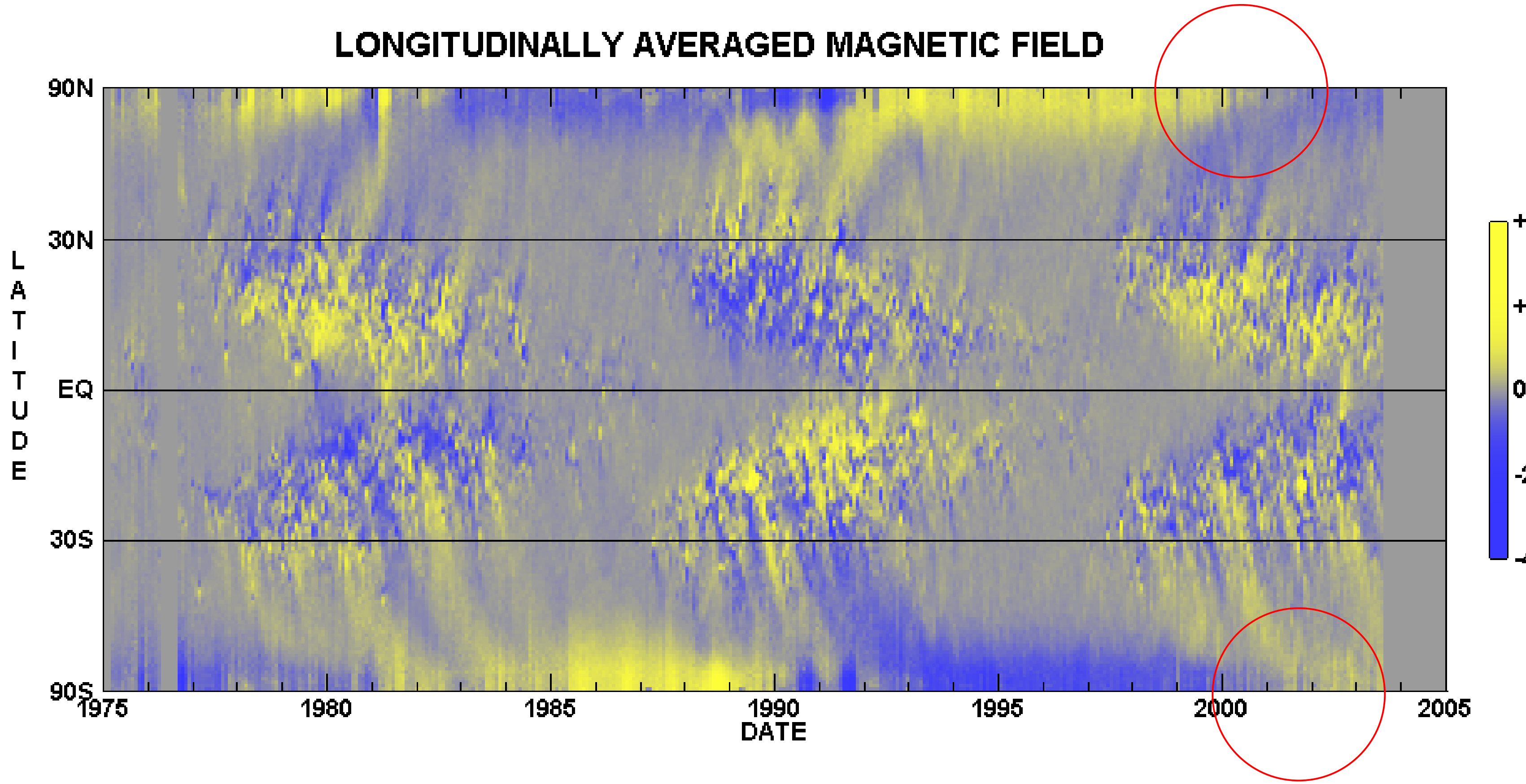
S

Polarity Reversal in Photospheric Field

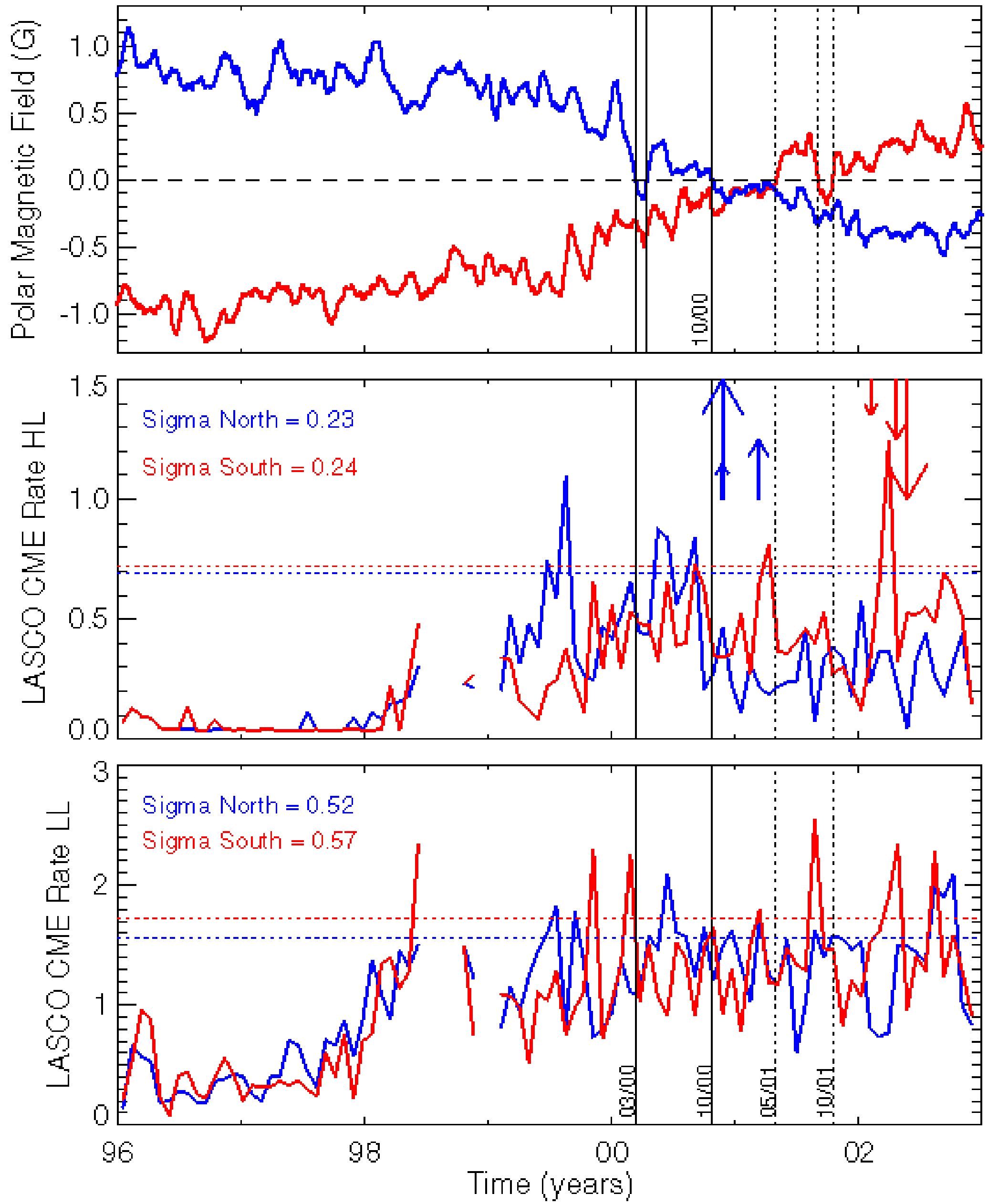


NASA/NSSTC/Hathaway 2003/09

Arrows: Lorenc et al. 2003; Harvey & Recely, 2003; Gopalswamy et al., 2003

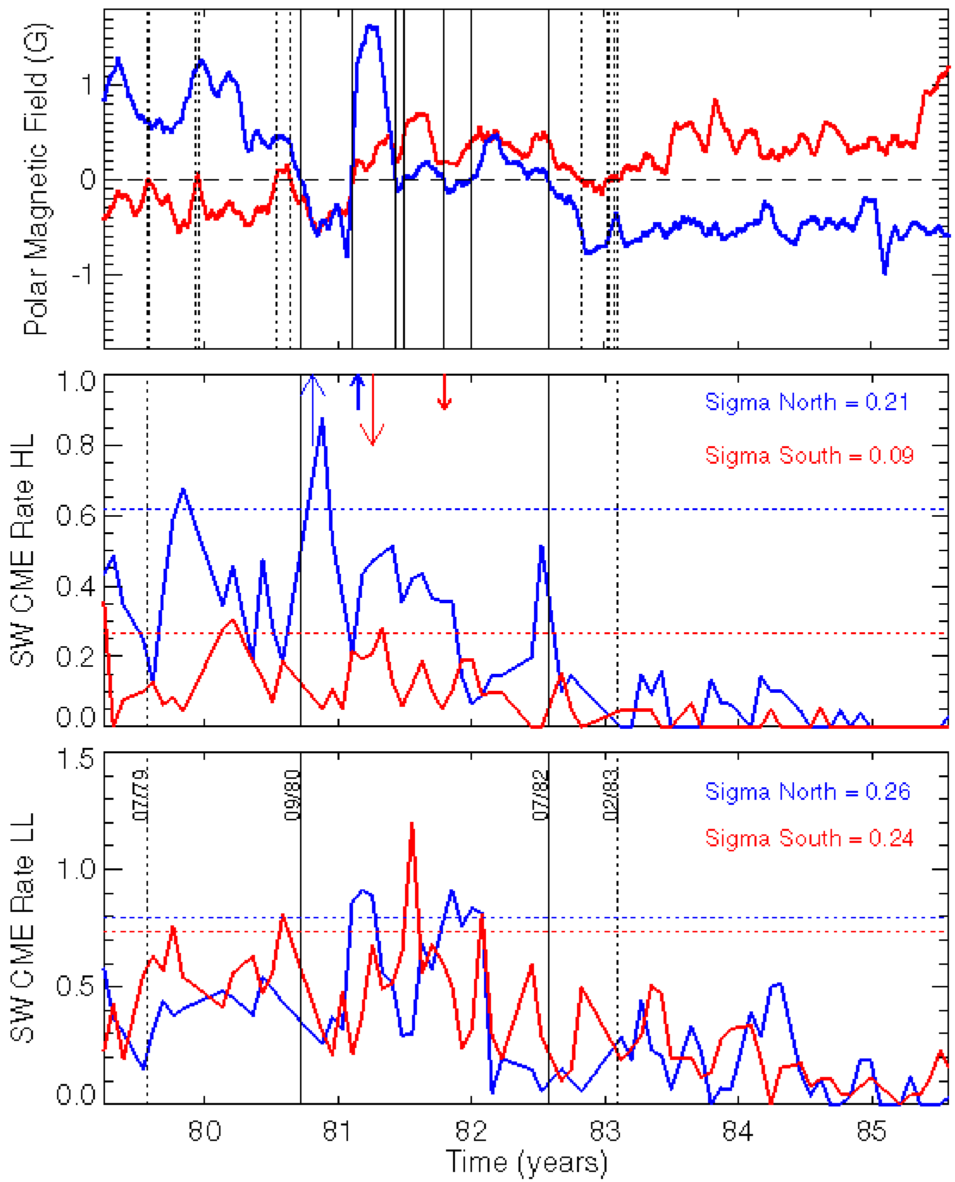
Cycle 23

- HL Rate picks up when pola B declines
- North polar reversal at the time of cessation of NHL CMEs
- South polar reversal 1.5 yr later, again coinciding with the cessation of SHL CMEs
- LL CME rate rather flat afte a step-like increase
- Consistent with the time of PCF disappearance



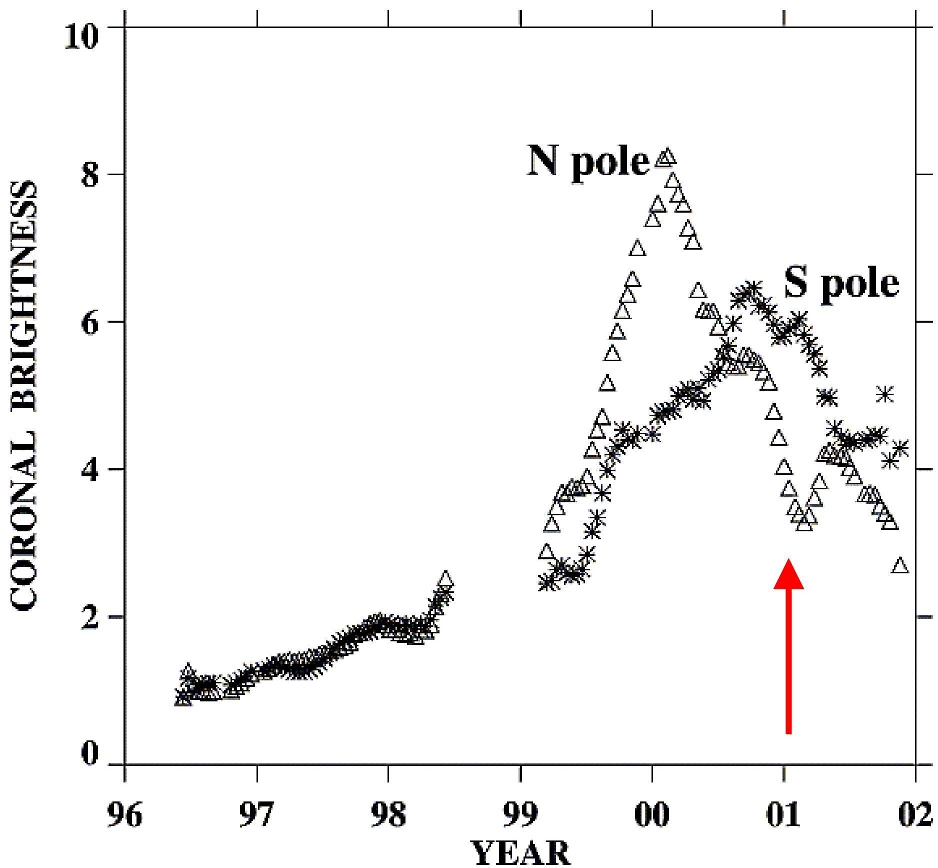
Cycle 21

- Solwind coronagraph on board P78-1 (corrected rates published by Cliver et al., 1994)
- PCF: Webb et al. 1984; Lorenc et al. 2003
- KPNO mag data
- CME cessation coincides with the polarity reversal



When are the reversals?

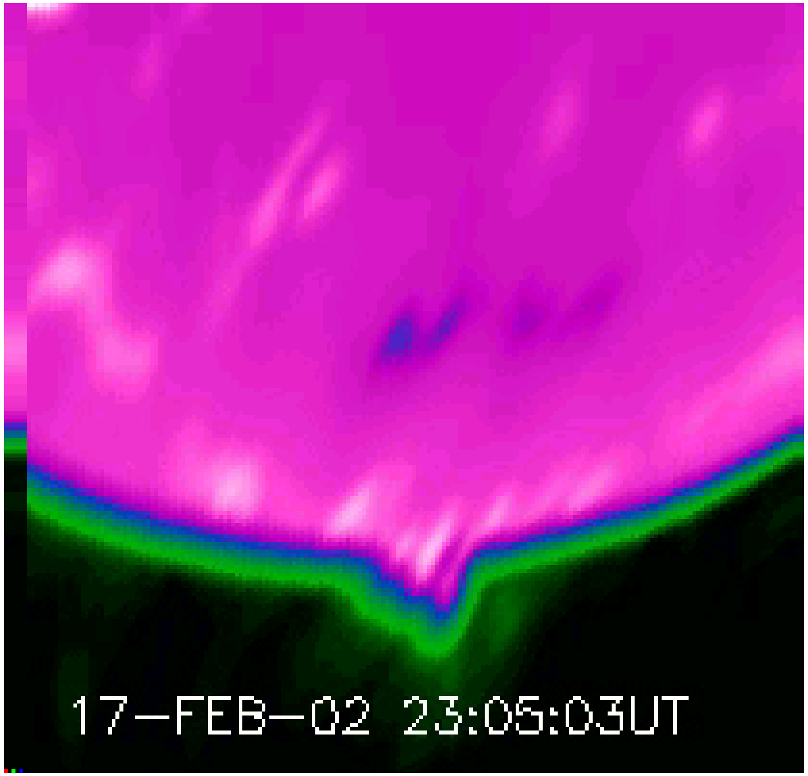
- HL streamer peak (Feb 2000) implies presence of HL closed structures. → reversal is not complete
- HL streamer brightness declines significantly towards the end of 2000 – agrees with CME cessation

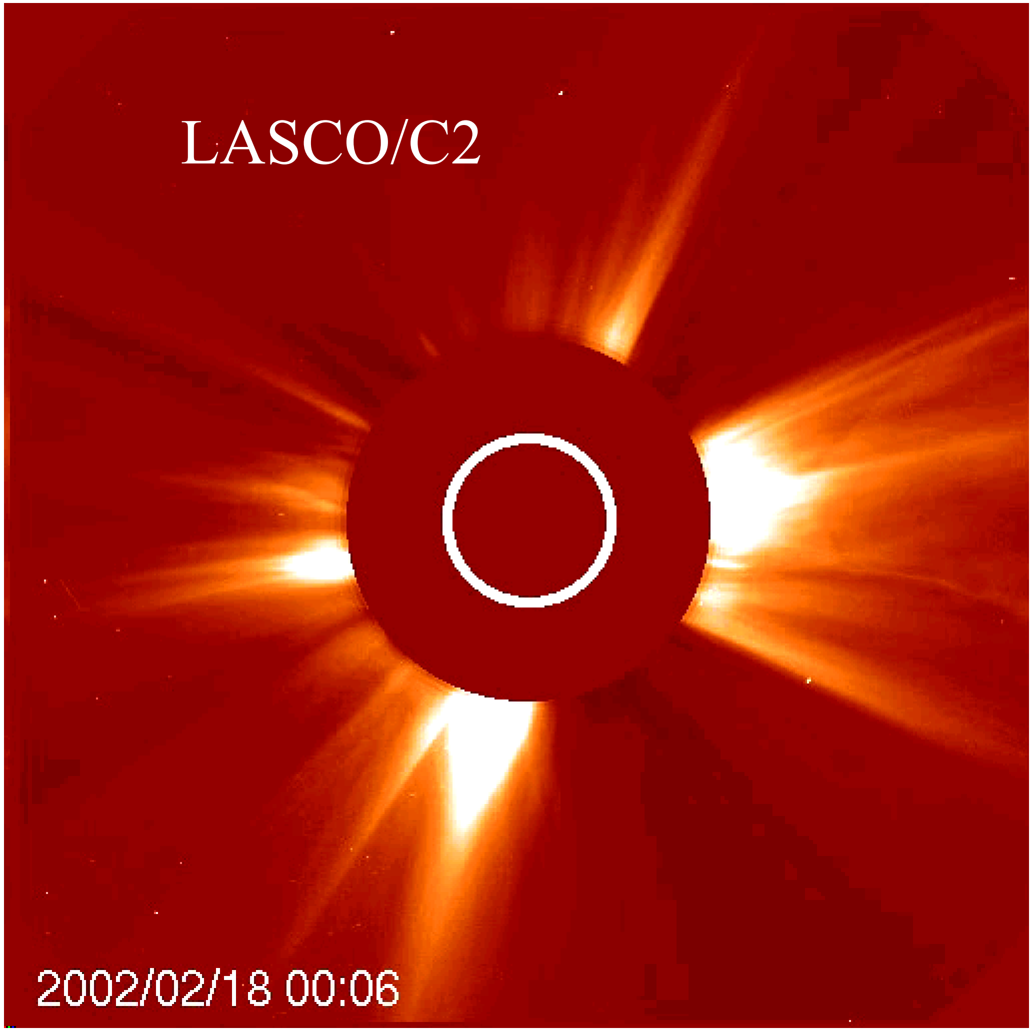


Wang, Sheeley & Andrews, 2002

A High-latitude CME & PCF

Nobeyama Radio Prominence

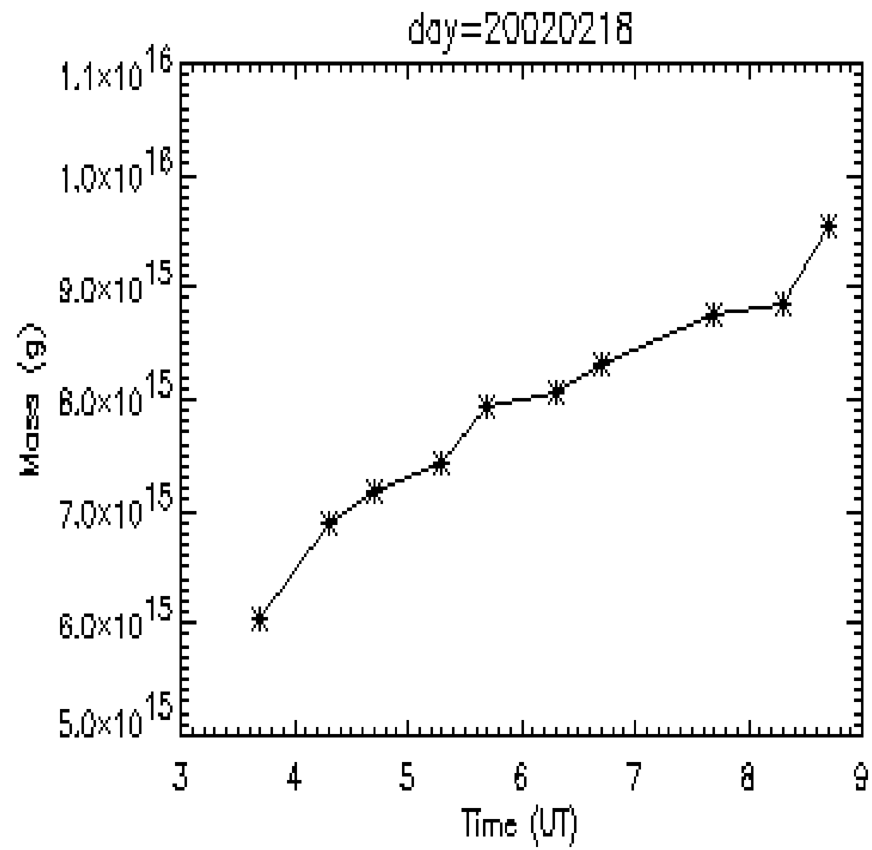




Energy involved in CMEs

- $M = 8.10^{15}$ g
- V=733 km/s
- $KE = 2.10^{31}$ erg
- It takes about 1200 CMEs over a period of 3 years to complete the polarity reversal

(2.10^{31} erg/day is dissipated)



Summary

- CME rate increases by an order of magnitude from min (0.5/day) to max (6/day)
- Max rate is almost twice the rates estimated for previous cycles
- Speed increases by a factor of ~2. This was not conclusive from pre-SOHO data. Now it is firmly establishd.
- Sunspot activity peaks in Jul 2000; CME activity peaks in Oct 2002
- Smoothed data show both sunspot and CME activity with a double peak. The first of the sunspot peak and the second of the CME peak are the largest. The second (largest) CME peak is also delayed with respect to the second sunspot peak.
- Correlation between SSN & CME activities can be better understood by separating high and low-latitude CMEs.
- The difference between sunspot activity and CME activity is due to the high-latitude CMEs, which are not associated with sunspots, but with polar crown filaments.
- Cessation of high-latitude CMEs and prominence eruptions are good indicators of polarity reversal including the north-south asymmetry in reversal
- CMEs may be the mechanism by which polarity reverses and involves dissipation of $\sim 2\ 10^{31}$ erg/day